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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled LOW PRESSURE DEHYDRATION OF WHEAT GRAINS submitted by GHULAM SARWAR in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE.

ABSTRACT

The objective of this project was to study the feasibility of drying grain at ambient air conditions but at pressures below atmospheric and compare this to the traditional ambient air drying system. The study method was to calculate the energy requirements per unit of moisture removed from the grain by the two systems. The dry and wet-bulb temperatures prevailing near Edmonton, Alberta, were used for the study. The results indicated that the energy requirements per kilogram of moisture removed are less for pressures below atmospheric than above, and that the energy requirements for pressures above atmospheric increase at a rate greater than the pressures below atmospheric when either the grain depth or airflow is increased. The number of hours available each day to dry grain to 14% moisture content were more and the number of days required to dry wheat were less using pressures below atmospheric for the usual drying period in Western Canada. Further research should continue that could lead to higher energy efficiency in grain drying.

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1. INTRODUCTION

In his recent book, Hall (1980) estimates the annual loss of grain after harvest to be 10% of the potential yield, and the loss of hay to be 28%. These estimates are for the United States; for many other countries the losses would exceed these figures. Moisture control, primarily by drying, provides an opportunity to reduce post-harvest losses.

Grain drying has become common across the Canadian prairies during recent years (Friesen 1978). Instead of drying only during wet harvest seasons, many farmers now use a drier as part of their normal grain harvesting system. There are a number of reasons for making drying an integral part of the harvesting system. Some of these include earlier harvesting by starting at higher moisture contents and thus reducing field losses due to shattering, wind and insects, and longer harvest days by using extra hours of harvesting in the morning and evening. It also permits the use of late-maturing cultivars and a more efficient use of land and labor. The grain quality produced can be superior which is worth more to both the farmer and the consumer.

The initial cost of the grain drier is one of the major deterrents to grain drying, but where large amounts of grain are dried, fuel efficiency is a more important factor. With the increasing interest in drying, such as cereal grains, and the increasing fuel prices, there is a need for investigations aimed at energy conservation in drying. This

study was undertaken; therefore, to see if there is a drying system that requires less energy.

2. LITERATURE REVIEW

The traditional method of drying farm crops is ventilating the grain with heated or unheated air. Based on a 1973 estimate, 3.8 million kiloliters (1005 million gallons) of LPG (liquid propane gas) was used for drying crops with heated air (CAST 1975). LPG is the most popular fossil fuel for grain drying in Canada and the United States. The ever-increasing fuel prices and possible shortages in future has made it necessary to use alternative fuels, to improve the efficiency of existing systems, and to develop new systems for energy conservation. The following is a brief review of the drying systems including the drying theory based on vapor pressure differential.

2.1 DRYING THEORY

Drying takes place when the vapor pressure within a hygroscopic material such as grain is greater than the vapor pressure of the surrounding medium (which is usually air). The equation presently used in calculating water vapor transmission through materials is based on a form of Fick's Law and is as follows (ASHRAE 1977) :

$$w = - u \, (dp/dx) \qquad (1)$$

Where w = weight of vapor transmitted through a unit area in unit time,

p = vapor pressure,

x = distance along the flow path,

(dp/dx) = vapor pressure gradient, and

u = permeability.

As shown by equation (1), if the vapor pressure in the grain is higher than the vapor pressure in the surrounding air, the transfer of moisture would be from grain to air thus effecting drying. Conversely, if the vapor pressure in the air is higher than the vapor pressure in the grain the transfer of moisture would be from the air to the grain thus increasing the grain moisture.

There are two methods of increasing the vapor pressure differential between the grain and the air. Traditionally in grain drying, the differential is increased by heating the air. As the hot air comes in contact with the grain, the latter is heated thereby increasing its vapor pressure. As will be shown later, the energy requirements of this method of drying are significant, and in industrialized nations, this method is largely dependent on fossil fuels. The other method of increasing the vapor pressure differential is used in food drying. Food processors use reduced air pressures to increase the vapor pressure differential. According to Dalton's Law, reducing the total air pressure will reduce the partial pressure of the dry air and the water vapor, and with a reduction in the latter, a vapor pressure differential will be increased (Todd 1981). This process has also high energy requirements but low pressure drying is

used to dry food because certain foods retain their characteristics of taste and nutritional quality better when dried under low pressure and low temperature than at high temperature. However, the drying apparatus for creating low pressure is expensive. Agricultural crops are not as sensitive to high temperature drying, so the less costly equipment is often selected by many farmers.

Researchers interested in grain drying have attempted to find a system that requires less energy than the heated air system traditionally used by the farmers. One system is based on ambient air where the air is pumped through the grain mass. Drying will occur because there is usually a small vapor pressure differential between the grain and the ambient air. This system is generally considered efficient but it has some other limitations which are discussed later in this chapter.

A number of researchers have studied the energy requirements of a variety of grain drying systems. The results of six most commonly used drying systems are discussed below in order to identify the typical energy requirements for grain drying.

2.2 HIGH TEMPERATURE DRYING

High temperature driers use a large flow of hot air to dry the grain in a period from less than an hour to several hours. Air temperatures range from 10°C above ambient to

80°C, the upper limit being determined by the grain and its intended use (Hall and Davis 1979).

The energy requirements for high temperature driers vary with drier design, drying temperature and airflow. A typical energy requirement is about 5000 KJ/kg of moisture removed (Hall 1980). The statistic includes the energy to heat the air and drive the fan with the fan energy representing about 10% of the total.

The quality of grain dried with heated air is often lower than that dried without heat (Foster 1973). The degradation of the grain quality characteristics such as viability or milling properties is a function of the air temperature. Higher air temperatures reduce the grain quality. Because of the reduced grain quality, and the high energy requirements with high temperature drying, other systems of drying are frequently used.

2.3 LOW TEMPERATURE AND AMBIENT AIR DRYING

Low temperature drying is a method of drying grain when small amounts of heat are added to increase the temperature a few degrees above the ambient. When no heat is added, it is called ambient air drying. Research has shown that low temperature and ambient air drying maintains the grain quality, and the energy requirements relative to conventional dryinf techniques are low (Gustafson et al. 1976; Morey et al. 1976).

Otten et al. (1977) performed some low temperature drying experiments near Guelph, Ontario, using corn. They reported a total energy input for heating the air and driving the fan from 3700 to 4400 kJ/kg. The main reason for the variation in the energy requirements was due to the higher airflow rates and a variation in ambient temperature (-17.5 to 9.5°C) during the drying period.

Morey et al. (1978A) conducted some drying experiments at three different locations (St. Cloud, Minnesota; Des Moines, Iowa; and Indianapolis, Indiana) to evaluate several fan management strategies for ambient air drying of corn. The energy requirements (fan only) varied from 900 to 2300 kJ/kg of water removed. In a similar study Morey et al. (1979) performed some experiments to evaluate the feasibility of ambient drying of wheat. They found the energy requirements (fan only) were 1700, 2000, and 2400 kJ/kg for Fargo, Grand Forks, and St. Cloud, Minnesota, respectively. These energy requirements are less than that reported for low temperature drying and much less than the commonly used conventional hot air driers. Also the minimum energy requirements are less than the latent heat of vaporization for grain moisture (2800 kJ/kg) as reported by Brooker et al. (1974). This is because the heat energy for vaporization comes largely from the sensible heat of the ambient air.

Despite the success obtained with low temperature and ambient air drying, it can be risky (Shove 1973A). The

wetter the grain, the greater the risk of spoilage. Any system for drying with little or no added heat should, therefore, be based on an understanding of the relationship between the temperature and the grain moisture content as to the number of days required to dry to a moisture content for safe storage. Fan energy requirements (the only energy source in case of unheated air) are significant because the fan has to operate for much longer periods of time than with low or high temperature drying.

2.4 COMBINATION (HIGH-LOW TEMPERATURE) DRYING

Combination drying is a system in which high temperature drying is followed by low temperature, or on occasion, ambient air drying. The purpose of high temperature drying is to reduce the grain moisture content to a level where drying can be completed without the risk of spoilage by low temperature and ambient methods. This system of drying has been used successfully in the corn belt in the United States. The advantages of combination drying are reduced energy requirements, increased drying capacity of the high temperature drier and improved grain quality (Morey et al. 1977; Morey et al. 1978B).

Morey et al. (1978C) conducted an extensive field scale evaluation of the combination drying system and found that the energy requirements range from 2100 to 3300 kJ/kg. In a similar test, Morey et al. (1980) reported energy

requirements in the range of 1800 to 3800 kJ/kg; the higher statistic occured when more moisture was removed in the high temperature phase than in the low temperature phase. The energy requirements are considerably less than the hot air driers, moderately higher than the ambient air drying and about the same for low temperature drying. As noted previously, the heat energy for vaporization comes largely from the sensible heat of the ambient air in the low temperature drying phase which reduces the total energy requirements compared to high temperature drying.

As was noted above the combination drying has been used successfully to dry corn but it may not be as advantageous for wheat because normally the latter has a lower moisture content when harvested.

2.5 SOLAR GRAIN DRYING

Grain drying is a process which can be easily adapted for the use of solar energy (Bauman and Finner 1979). With the uncertainty of future supplies and the increases in the cost of fossil fuels, solar energy is of interest as a source of energy for grain drying (Feddes et al. 1980). One major factor considered in the installation of a solar drying system is the capital cost. For example, Johnson and Otten (1980) found that the fixed costs of the collector were sufficiently high to make solar assisted drying more expensive than both ambient drying and conventional high

temperature drying even though the energy cost was lowest for solar drying. McLean (1980) reported that while it is extremely pertinent that research should be carried out in anticipation of rising fuel costs, at the present time the installation of solar panels for use in conjunction with storage drying systems is uneconomical. Hall and Davis (1979) expressed similar views and stated that solar energy systems have the potential for minimizing energy requirements but their economic justification at the time is marginal.

Peart et al. (1980) reported fan energy requirements of 1800 to 2400 KJ/Kg for solar drying of corn in Indiana. Though these energy requirements are considerably less than the commonly used hot air driers they are approximately the same as ambient air drying. The reason may be due to the solar energy gain being offset by the higher friction losses in the solar panels and the additional ducts. One advantage of solar drying over ambient air drying is a higher drying rate and, therefore, the potential of solar drying should not be neglected in future research on grain drying.

2.6 MICROWAVE VACUUM DRYING

Vacuum drying has been used for dehydrating some agricultural products but is usually restricted to foods where quality is important and; therefore, must be dried at relatively low temperatures. As for drying cereal grains

under vacuum there is no data available with the exception of MIVAC, the experimental microwave vacuum drying system developed recently by McDonnell Douglas Corporation in the United States (Gardner and Butler 1980).

In MIVAC drying, high vacuum and microwave energy are used to dry materials quickly and at temperatures somewhat less than the high temperature driers. The material to be dried is loaded into a drying chamber which is then isolated from the ambient pressure environment. The chamber is evacuated to the desired pressure, most commonly 3.4 to 6.6 kPa (standard atmospheric pressure is about 101.5 kPa). During drying, the material flows from an upper hopper through the drying zone under vacuum, and into the lower hopper where the dried material is collected.

A number of experiments were conducted by Gardner and Butler (1980) over a sixteen month period to dry many different crops such as corn, peanuts, sorghum, rye, and rice using MIVAC dryer. The energy requirements were in the order of 600 to 1000 kJ/kg of moisture removed which are considerably less than the conventional hot air driers and somewhat less than any other drying system. Another microwave grain drier has been introduced by Ken Bratney Company of Des Moines, Iowa (Stauffer). This drier basically works on the same principles as the MIVAC system, and according to the manufaturer, it uses about 125 to 475 kJ/kg of moisture removed from soybeans. The commercial success of the drier is assured if the energy requirements are as

claimed.

The energy requirements for crop drying using microwave vacuum methods appears considerably less compared to other drying methods (as quoted by the two manufacturers); however, one major factor that a farmer considers is the initial cost. As reported by Bakker-Arkema et al. (1978), the initial cost is not competitive with conventional driers. Boulanger et al. (1969) suggests that the cost of a farm sized unit which can process 7 cubic meters of grain per hour (200 bu/hr) is in the order of $150,000 to $350,000. Another important factor limiting the use of microwave vacuum drying, is the use of electric energy for its megnetron unit. It has been shown by Morrison (1978) that electricity is still a relatively expensive form of energy; at least twice the equivalent of heat energy of fossil fuels. Also a skilled operator and good management appear to be required to operate this system. Due to these factors and the possibility of high maintenance costs, the use of these driers on individual farms seems unlikely in the near future unless the efficiency is extremely good.

2.7 SUMMARY AND OBJECTIVE

The energy requirements for a number of drying systems have been reported and discussed. They are :

1.	High Temperature	5000 (kJ/kg water)
2.	Low Temperature	3700-4400
3.	Combination	1800-3800
4.	Solar	1800-2400
5.	Ambient	900-2400
6.	Microwave Vacuum	600-1000

The energy requirements for high temperature grain drying are almost double the latent heat of vaporization of water and are higher than any other system in use whereas the energy requirements for vacuum drying system using microwaves were the lowest. Largely because of the capital costs, the focus will likely be on improving the efficiency of the other systems.

The previous discussions show that the energy requirements for ambient air drying are about same or less than the latent heat of water vaporization. As mentioned earlier, this method is generally considered efficient as the heat for water vaporization comes largely from the ambient atmosphere. One major problem with this method is the lower drying rate which causes a higher risk of spoilage.

The ambient air systems usually have deep beds of grain which results in a significant pressure gradient across the grain. A fan is used to provide the pressure so that air

enters the bin at pressures higher than atmospheric and leaves at atmospheric pressure. Drying occurs on the basis of the ambient air conditions at atmospheric pressure. Since decreasing the total pressure will increase the vapor pressure differential and since the air movement through grain is based only on the static pressure difference across the grain, one would expect that the drying capacity of an ambient air system could be increased without affecting the energy input by placing the fan on the outlet of the grain bin rather than at the inlet. In such a system, the pressure inside the grain bin will be slightly below atmospheric (for example in the order of 85 to 93 kPa). The heat energy for water vaporization will be provided by the ambient air. If the energy requirements are comparable to the traditional ambient drying system then this system may prove a better alternative; consequently, the potential of this system should be investigated.

Based on the above discussions, the objective of this project was to study the feasibility of drying grain with air at ambient temperature but with pressure less than atmospheric and compare this to the traditional ambient air drying method. The basis for comparison is the energy required to evaporate one kilogram of water.

3. PROCEDURE

3.1 INTRODUCTION

Two ambient drying systems (above and below atmospheric pressure) were studied for the common drying period in Western Canada of August through November. The grain considered was wheat because of the large quantity grown in Western Canada. The study method was to calculate the energy requirements for removing moisture from the grain by the two systems. The dry-bulb and wet-bulb temperatures (t and tw respectively) prevailing near Edmonton, Alberta, as given by Cudbird (1964), were used for the study (Appendix A). These temperatures were monthly averages for every hour of each day for the four months mentioned above.

Seven different pressures were considered for this study, with four below and three above atmospheric. These pressures were 86.7, 88.4, 90.1, 91.8, 95.2, 96.9, and 98.5 kPa while the atmospheric pressure as given by Cudbird (1964) was 93.5 kPa. Three below atmospheric pressures correspond to three of the four above atmospheric pressures; having same magnitude above and below the atmospheric pressure. They were selected to compare the two systems. These pressures represent a pressure drop of 1.7, 3.4, 5.1, and 6.8 kPa through grain having depths of approximately 1.0, 1.3, 1.6, and 1.9 meters respectively when an airflow of 3 m^3/min-tonne is used (Hukill and Shedd 1955). A

pressure drop of 6.8 kPa above atmospheric was not considered practical. The energy requirements for a system operating at atmospheric pressure are not included because any practical drying system must have some pressure loss in order to have air movement.

Eight initial moisture contents were selected for each moisture content from 15% to 22% and the final moisture content of 14%. These values cover the most likely range of moisture contents at harvest in Western Canada.

3.2 ASSUMPTIONS

A number of assumptions were necessary to calculate the energy requirements. They are :

1) Expansion for the below atmospheric or exhausting system and compression for the above atmospheric or pressurizing system is isothermal; that is, sufficient heat is gained or lost to the surroundings to maintain the temperature in the plenum at the ambient temperature (see figure 1).
2) No change in enthalpy occurs as the air passes through grain.
3) The airflow is low enough that the air leaves grain at the equilibrium relative humidity (ERH).

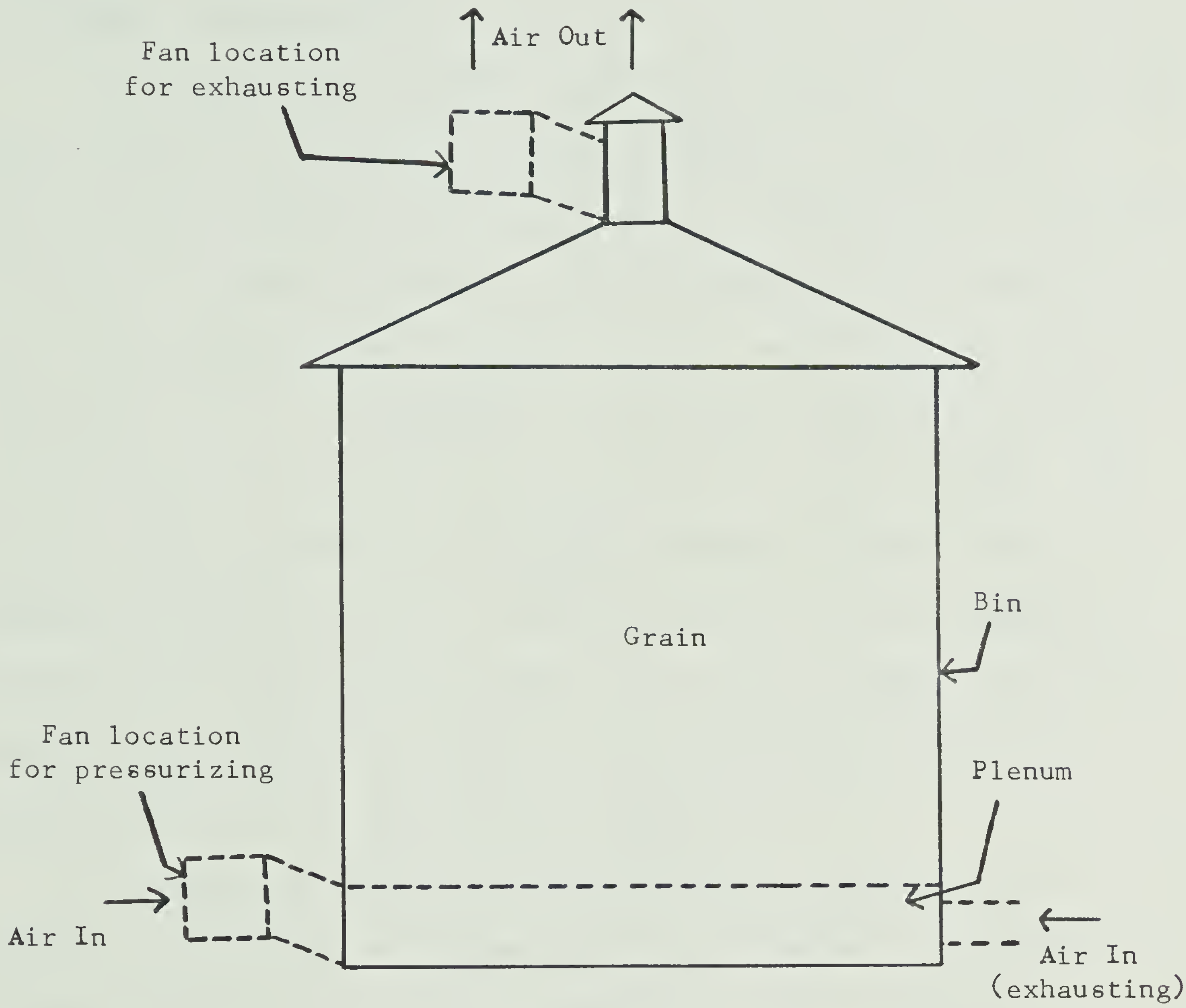

Figure 1: Schematic diagram representing the two drying systems.

4) There is a pressure gradiant across the grain mass.

5) The fan is adiabatic.

3.3 ENERGY CALCULATIONS

The energy requirements were calculated on the basis of water removed from grain. The fan energy (E) required to move air through grain was defined as Kilojoule per Kilogram of dry air (KJ/Kg dry air). The difference in the humidity ratio (Kg water/Kg dry air) of the air entering and leaving the grain (ΔX) is the amount of moisture removed by the air from the grain (figure 2) as noted by Harrison (1969). The figure indicates the relationship between ΔX and the air temperature entering and leaving the grain which depends on the ERH. Dividing the two quantities ($E/\Delta X$) would yield the energy requirements in terms of heat energy per unit of moisture removed (KJ/Kg water removed).

A computer program was developed to calculate the various psychrometric properties of air before and after drying. Calculations for the humidity ratio of the air leaving grain (X') required the use of an iterative procedure. A complete listing of the program is provided in the Appendices D and E.

The change in the humidity ratio of the air during drying (ΔX) was calculated for various moisture content ranges (22-14%, 21-14, etc. through 15-14%) for the four

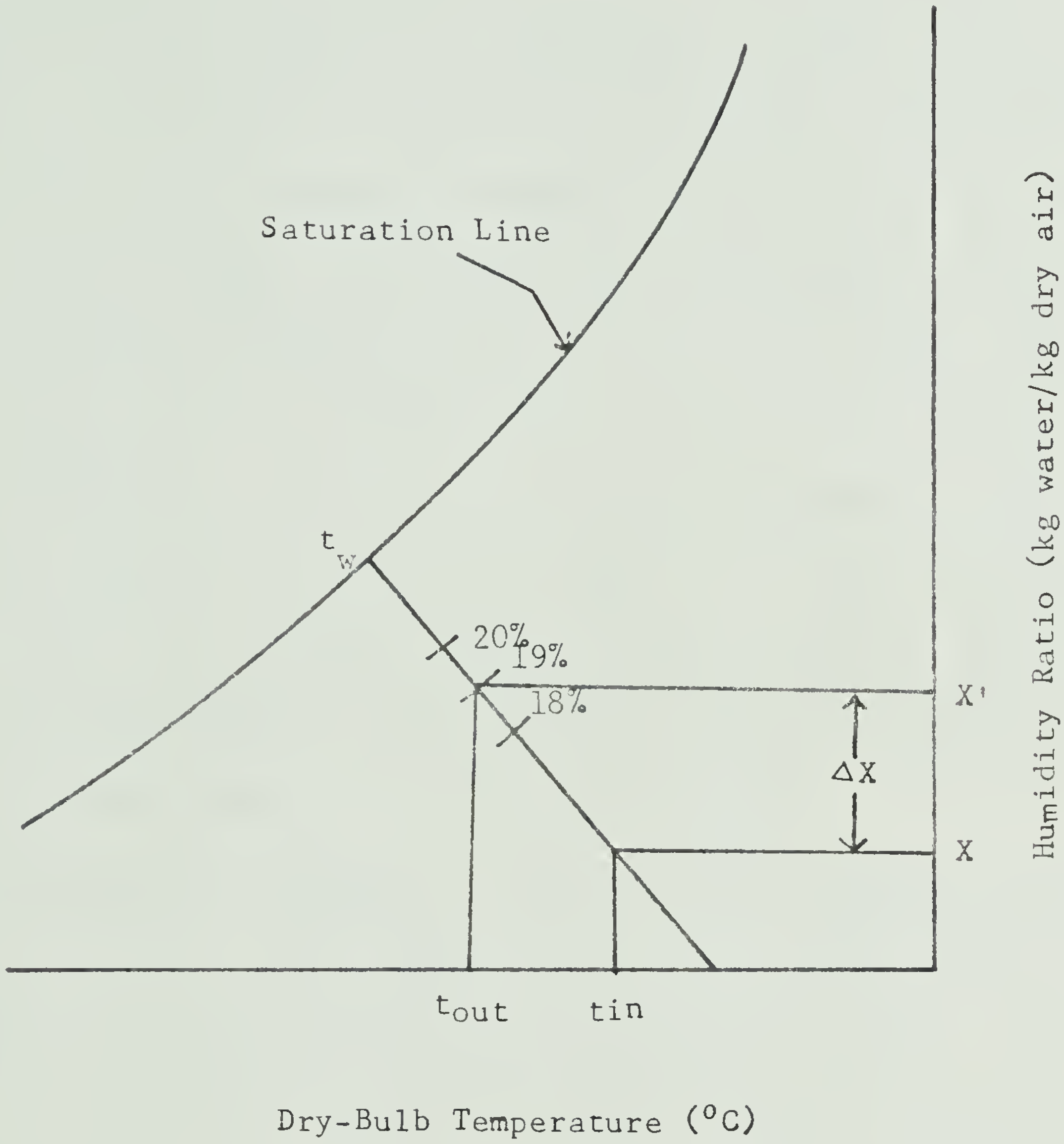

Figure 2: Psychrometric Chart

drying months by using a procedure suggested by Harrison (1969). The dry-bulb and wet-bulb temperatures (t and tw respectively) used for these calculations were monthly averages as given by Cudbird (1964). If ΔX was positive, the air had a drying potential; otherwise it had a wetting potential. The moisture removal per day was determined by dividing the sum of positive humidity ratios by the number of hours the changes were positive, and repeating this for moisture content changes of 22 to 21%, 21 to 20%, and so on until 15 to 14%. For the moisture range 16 to 14% the moisture removal (ΔX) for 16 to 15% was added to the moisture removal for 15 to 14%. For 17 to 14% the moisture removal for 17 to 16% was added to the moisture removal for 16 to 14% and repeating in a similar manner to obtain the moisture removal for all the other ranges.

The change in energy of the air as it passes through an adiabatic fan was calculated for the four pressures below atmospheric and three above as mentioned earlier. The air temperature used for these calculations was the average dry bulb temperature of all the hours when ΔX is positive.

The procedure for calculating ΔX and E is noted below and is presented in a flow chart in Appendix G :

STEP 1

The equilibrium relative humidity ERH (%) for wheat was calculated from Chung's equation

(Pfost et al. 1976; Appendix B) :

$$ERH = \exp((-A/(t+C)) \exp(-B\ M)) \quad (2)$$

Where M = grain moisture content (%),

t = dry-bulb temperature (°C),

A = 529.43 (hard wheat),

B = 17.609, and

C = 50.998.

STEP 2

The ERH values were determined using the dry-bulb temperatures prevailing near Edmonton as given by Cudbird (1964) and the hard wheat at nine moisture contents of 14 through 22%. The array of ERH values was 4 x 24 x 9. The ERH values along with the dry and wet-bulb temperatures were stored in a computer file (Appendix C).

STEP 3

The saturation vapor pressure of the air Pws (atmospheres) over ice for the temperature range of -100°C to 0°C was calculated from (ASHRAE 1977) :

$$\log(Pws) = -9.096936(\theta-1)-3.56654\log(\theta) +0.876817(1-(1/\theta))-2.2195983) \quad (3)$$

and for the temperature range of 0°C to 100°C was calculated from (ASHRAE 1977) :

$$\log(Pws) = 10.79586(1-\theta)+5.02808\log(\theta) +0.00015(1-10^{-8.29692((1/\theta)-1)}) +0.00042873(10^{4.76955(1-\theta)}-1) -2.219598 \quad (4)$$

Where θ = 273.16/(tw+273.16), and

tw = wet-bulb temperature (°C), (Cudbird 1964).

STEP 4

The humidity ratio of the air at saturation Xs (lb water/lb dry air) was calculated from (ASHRAE 1977) :

$$Xs = 0.62198Pws/(B - Pws) \quad (5)$$

and B = (Bf + Batm)/2

Where B = mean pressure in grain mass (kPa),

Bf = one of the seven fan pressures (kPa), and

Batm = atmospheric pressure (93.5 kPa).

STEP 5

The enthalpy of the air H (kJ/kg) was calculated from (McQuiston and Parker 1977) :

$$H = tw + Xs(2503.1 + 1.86tw) \qquad (6)$$

STEP 6

The humidity ratio of the air X (lb water/lb dry air) was calculated by rearranging equation (5) and also replacing tw by t.

$$X = (H - t)/(2503.1 + 1.86t) \qquad (7)$$

The humidity ratio before and after compression or expansion does not change.

STEP 7

The heat gained by the grain or change in enthalpy of the air during the isothermal expansion Q (kJ/kg), was calculated from (Moyer et al. 1941) :

$$Q = R(t+273.16)\,ln(P1/P2) \qquad (8)$$

Where P1,P2 = pressures at the inlet and exhaust (kPa), and

R = universal gas constant.

Therefore, the enthalpy of air (kJ/kg dry air) after the isothermal expansion is (H') :

$$H' = H + Q \tag{9}$$

There was no change in the enthalpy of the air for compression because the heat was assumed to be lost to the surroundings; that is, isothermal compression.

STEP 8

The humidity ratio X' (kg water/kg dry air) of the air leaving grain was calculated as follows :

i) calculate tout = H'/Ca

where Ca = specific heat of dry air (kJ/kg °C), and

tout = temperature of air leaving grain (°C).

ii) decrement tout by 1°C

iii) calculate Pws at tout per equation (3) or (4)

iv) calculate Xs per equation (5)

v) calculate H per equation (6)

vi) calculate X' per equation (7)

vii) calculate the relative humidity

RH (%) by (ASHRAE 1977) :

$$RH = 100(X'/Xs)/(1-(1-(X'/Xs)Pws/B)) \qquad (10)$$

viii) go to step (ii) and repeat steps (ii) to (vii) until RH is equal to ERH. The dry-bulb temperature of step (ii) and the humidity ratio of step (vi) in the final loop is the temperature and the humidity ratio (X') of the air leaving grain.

STEP 9

Calculate ΔX or $(X'-X)$ then go to step (ii) and repeat steps (ii) to (viii) for all the nine ERH values at this dry-bulb temperature. Each ERH value corresponds to a equilibrium moisture content (Appendix C).

STEP 10

Repeat steps (3) to (9) for all the dry-bulb temperatures to fill the array (4 x 24 x 9).

STEP 11

Repeat steps (3) to (10) for all the seven pressures to fill the array (4 x 24 x 9 x 7).

STEP 12

Sum the positive ΔX values for each hourly temperature for the various initial moisture contents of 22%, 21%, until 15%. The hours (T) when ΔX is positive were also summed. Dividing $\Sigma\Delta X$ by T, the average value of $\overline{\Delta X}$ for the day when it is positive is obtained.

STEP 13

Calculate the ΔX values for different initial moisture content ranges of 22 to 14%, 21 to 14% through 15 to 14% by accumulating the values of the drying potential as noted previously.

STEP 14

Determine the number of hours (T) available to dry each day for different moisture content ranges of 22-14%, 21-14%, through 15-14% by using the cummulative values of T. The procedure followed was similar to the one for ΔX.

STEP 15

The number of days (D) required to dry grain from various initial moisture contents to

14% were calculated by (Feddes et al. 1980; Harrison 1969) :

$$D = V\ Ww\ \Delta W/q/T\Delta X \qquad (11)$$

and $$W = Mw - Mw'(1-Mw)/(1-Mw') \qquad (12)$$

Where V = specific volume of dry air ($0.81\ m^3/Kg$),

Ww = weight of grain (1000 Kg/tonne),

q = airflow rate ($3\ m^3$/min-tonne),

$T\Delta X$ = kg moisture-min/kg dry air-day,

ΔW = amount of moisture removed (kg),

Mw = initial moisture content (%), and

Mw' = final moisture content (%).

These equations are used in the computer program shown in Appendix F.

STEP 16

The change in energy of the air E (KJ/Kg dry air) after it passes through an adiabatic fan was calculated from (De Nevers 1971) :

$$E = (R(t+273.16)k/(k-1))((P2/P1)^{(k-1)/k}-1) \qquad (13)$$

Where P1,P2 = pressures at the inlet and exhaust (kPa),

R = universal gas constant, and

k = 1.4

STEP 17

The energy requirements for drying the grain (kJ/Kg water removed) were calculated by dividing E by ΔX.

4. DISCUSSION OF RESULTS

The energy required to remove one kilogram of moisture, the number of hours per day when drying can occur, and the number of days required to dry wheat to 14% are shown in tables 1, 2 and 3. Table 1 shows that some of the energy requirements per kilogram of moisture are less than the latent heat of vaporization for grain moisture (2800 kJ/kg) as given by Brooker et al. (1974). As noted in chapter 2, much of the latent heat for vaporization comes from ambient air and is not included in the energy calculations. Table 2 shows that more hours per day are available for drying when the pressure is below atmospheric than above. In addition, drying to 14% on a 24 hour basis is possible for any of the four drying months if the pressure is 88.4 kPa or less. This is particularly significant for the month of November when grain cannot be dried to 14% in the conventional manner (above atmospheric pressure) using ambient air. Table 3 indicates that the number of days required to dry wheat from various initial moisture contents to 14% are generally less for pressures below atmospheric than above. Also table 3 indicates that drying to 14% cannot be completed during October at 22% initial moisture content and at any initial moisture content during November for the above atmospheric pressures.

The energy requirements for the months of August, September, and October at three initial moisture contents of 15, 18, and 21% are shown graphically in figures 3, 4, and

Table 1

Energy Requirements (kJ/kg water removed) for drying wheat under the ambient air conditions and at pressures above and below atmospheric

Atmospheric pressure = 93.5 kPa

Month	Pressure (kPa)	Moisture Content Range (% w.b.) 22-14	21-14	20-14	19-14	18-14	17-14	16-14	15-14
August	98.5	4650	4770	4870	4920	5010	5180	5524	6060
	96.9	3050	3130	3210	3250	3290	3420	3570	3900
	95.2	1490	1530	1570	1590	1600	1660	1720	1880
	93.5								
	91.8	1330	1380	1440	1510	1570	1590	1600	1680
	90.1	2330	2430	2530	2660	2800	2930	2940	3100
	88.4	3130	3260	3420	3620	3860	4170	4480	4490
	86.7	3700	3850	4030	4250	4542	4920	5420	5960
September	98.5	5580	5740	5880	5960	6010	6270	6530	6940
	96.9	3740	3870	4000	4100	4150	4270	4410	4940
	95.2	1830	1890	1960	2010	2040	2070	2140	2370
	93.5								
	91.8	1600	1670	1750	1840	1920	1960	2010	2070
	90.1	2830	2960	3130	3330	3580	3830	3980	4080
	88.4	3700	3870	4090	4350	4680	5090	5520	5490
	86.7	4360	4540	4780	5070	5460	5950	6590	7220
October	98.5	6650	6930	7230	7490	7710	7780	8060	8690
	96.9	4400	4600	4810	5020	5220	5260	5410	5590
	95.2	2170	2270	2380	2490	2610	2630	2740	2990
	93.5								
	91.8	1880	1980	2100	2240	2400	2530	2560	2610
	90.1	3260	3420	3630	3880	4200	4540	4780	4710
	88.4	4290	4500	4760	5100	5530	6070	6680	7140
	86.7	5080	5320	5620	6000	6520	7210	8280	9510
November	98.5*								
	96.9*								
	95.2*								
	93.5								
	91.8	4230	4630	5180	5920	6850	7770	7950	10180
	90.1	6670	7230	7970	9010	10430	12310	13710	14320
	88.4	8210	8850	9710	10880	12570	15120	18830	20990
	86.7	9110	9740	10570	11700	13300	15740	19730	25920

* Drying to 14% moisture content cannot be achieved at the above atmospheric pressures.

Table 2

Number of hours per day available for drying wheat under the ambient air conditions and at pressures above and below atmospheric

Atmospheric pressure = 93.5 kPa

Month	Pressure (kPa)	Moisture Content Range (% w.b.)							
		22-14	21-14	20-14	19-14	18-14	17-14	16-14	15-14
August	98.5	19	18	17	16	14	13	12	11
	96.9	19	18	17	16	15	13	12	11
	95.2	19	18	17	16	15	13	12	11
	93.5								
	91.8	21	21	20	20	19	17	15	13
	90.1	22	22	21	21	20	19	17	15
	88.4	23	23	23	23	22	22	21	18
	86.7	24	24	24	24	24	23	23	22
September	98.5	18	18	17	15	13	12	11	9
	96.9	19	18	17	16	14	13	11	10
	95.2	19	18	17	16	15	13	11	10
	93.5								
	91.8	21	21	20	19	18	16	14	12
	90.1	22	22	22	21	21	20	18	15
	88.4	23	23	23	23	22	22	21	17
	86.7	24	24	24	23	23	23	23	21
October	98.5	19	18	17	16	14	12	11	9
	96.9	20	19	18	17	15	13	11	9
	95.2	20	19	18	17	16	13	12	10
	93.5								
	91.8	22	21	21	20	19	17	15	12
	90.1	22	22	22	21	21	20	18	14
	88.4	23	23	23	23	22	22	21	18
	86.7	24	24	24	24	24	24	24	23
November	98.5*								
	96.9*								
	95.2*								
	93.5								
	91.8	20	19	18	17	16	13	8	6
	90.1	21	21	20	19	18	16	13	8
	88.4	23	22	22	22	21	20	19	13
	86.7	24	23	23	23	23	23	22	20

* Drying to 14% moisture content cannot be achieved at the above atmospheric pressures.

Table 3

Number of days required to dry wheat under the ambient air conditions and at pressures above and below atmospheric

Atmospheric pressure = 93.5 kPa

Month	Pressure (kPa)	Moisture Content Range (% w.b.)							
		22-14	21-14	20-14	19-14	18-14	17-14	16-14	15-14
August	98.5	23	21	19	18	16	13	10	6
	96.9	22	20	19	17	15	13	10	6
	95.2	21	20	18	16	15	12	10	6
	93.5								
	91.8	17	15	14	13	11	9	7	4
	90.1	14	13	12	10	9	8	6	3
	88.4	12	11	10	9	8	6	5	3
	86.7	10	9	8	7	6	5	4	2
September	98.5	28	26	25	23	21	18	14	9
	96.9	27	26	24	22	20	17	14	8
	95.2	26	25	23	21	19	17	13	8
	93.5								
	91.8	21	19	18	16	14	12	10	6
	90.1	17	16	14	13	12	10	8	5
	88.4	14	13	12	11	9	8	6	4
	86.7	12	11	10	9	9	6	5	3
October	98.5	**	**	29	27	25	22	18	11
	96.9	**	30	28	26	24	21	17	9
	95.2	**	29	27	25	23	21	17	10
	93.5								
	91.8	24	23	21	19	17	15	12	7
	90.1	20	19	17	16	14	12	9	6
	88.4	17	16	14	13	11	10	7	5
	86.7	14	13	12	11	9	8	6	4
November	98.5*								
	96.9*								
	95.2*								
	93.5								
	91.8	**	**	**	**	**	**	**	**
	90.1	**	**	**	**	**	**	**	**
	88.4	**	**	**	29	28	26	24	19
	86.7	27	25	24	22	20	18	17	11

* Drying to 14% moisture content cannot be achieved at the above atmospheric pressures.
** Drying to 14% moisture content cannot be achieved during one month period.

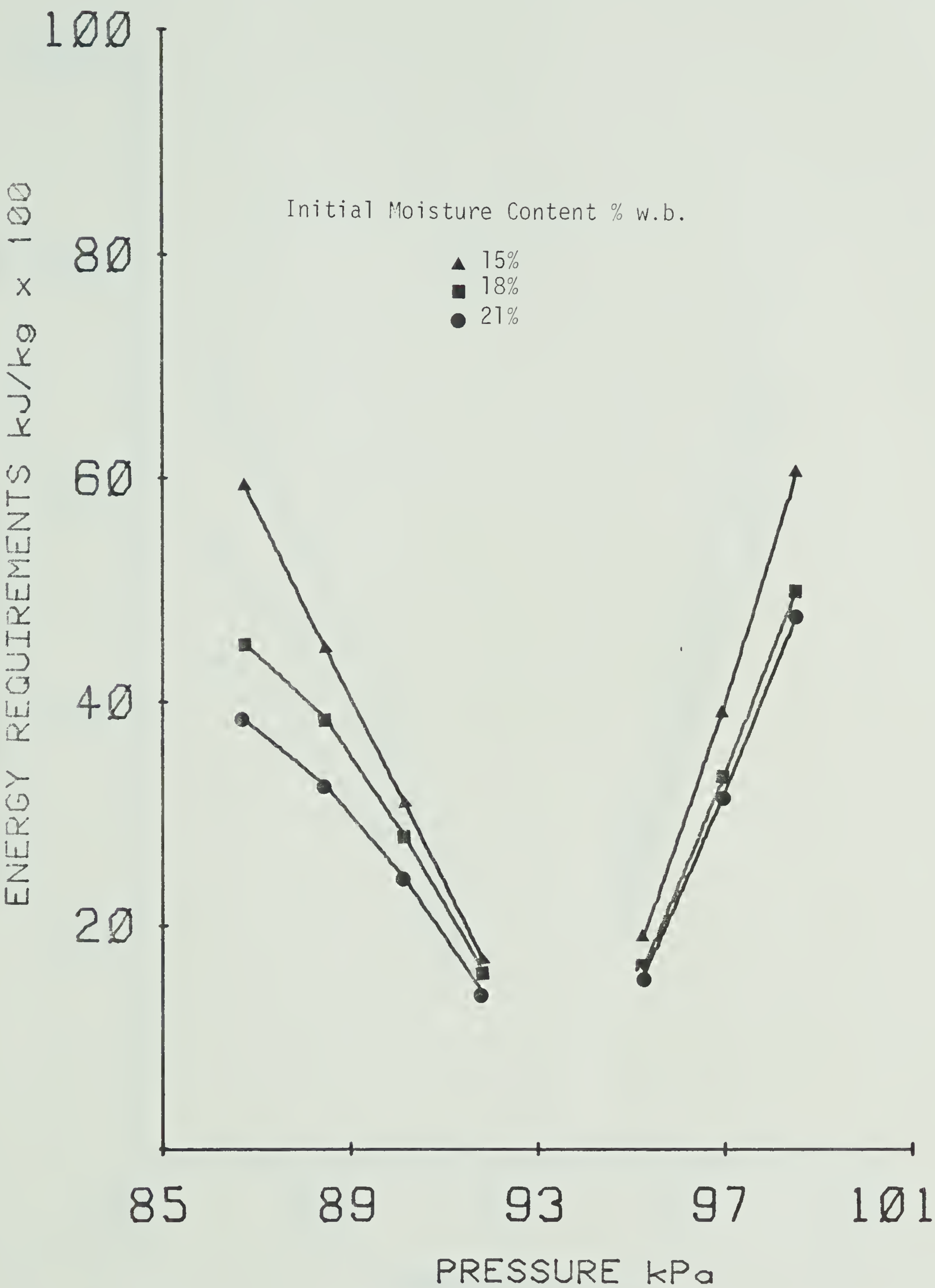

Figure 3: Effect of Pressure and Initial Moisture Content on the Energy Requirements during August

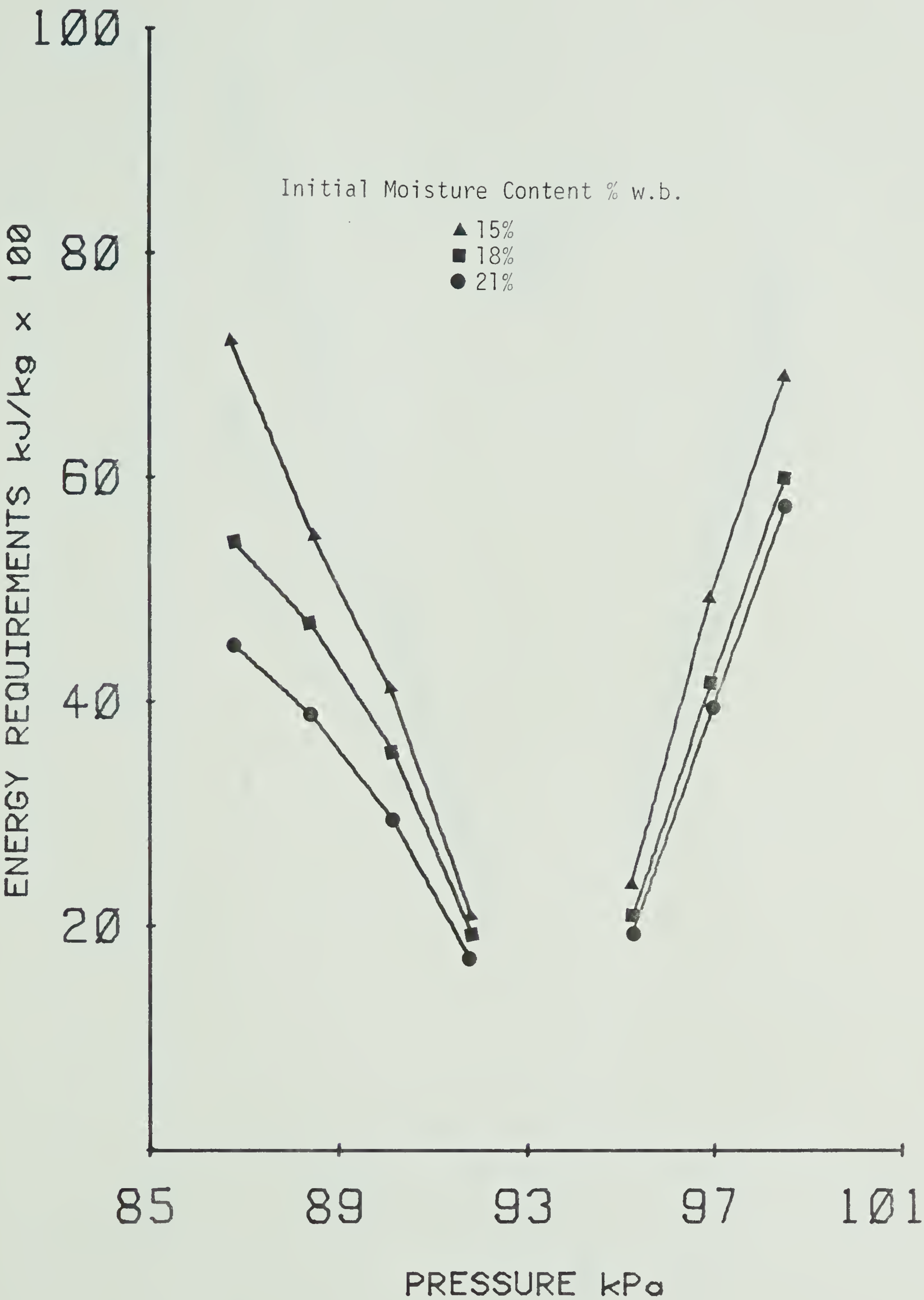

Figure 4: Effect of Pressure and Initial Moisture Content on the Energy Requirements during September

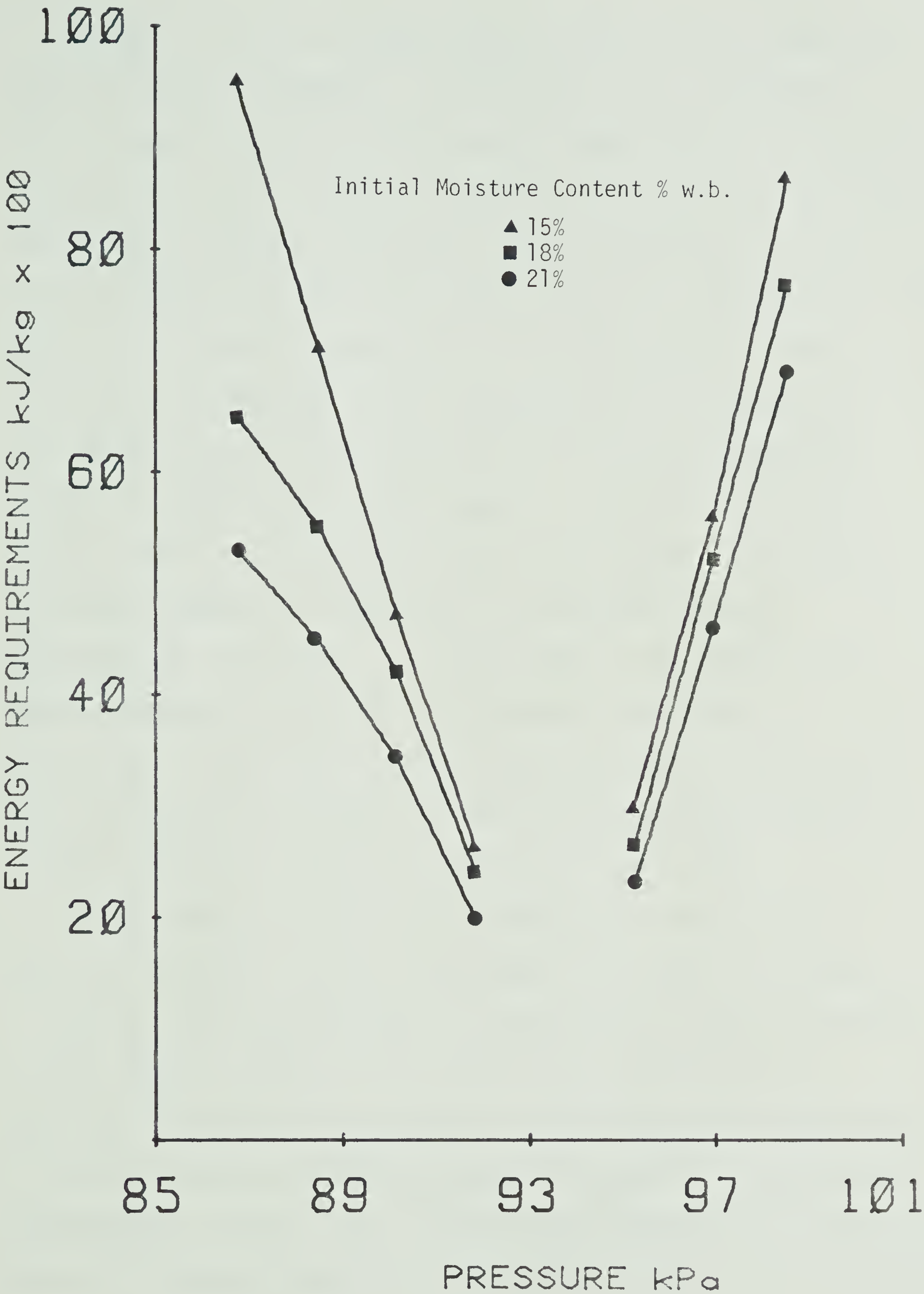

Figure 5: Effect of Pressure and Initial Moisture Content on the Energy Requirements during October

5. November is not included since drying to 14% cannot be achieved during November at pressures above atmospheric. These figures show that the energy requirements increase as the pressure drop through the grain increases for both the ambient air systems evaluated. The increases for either pressurizing or exhausting (above and below atmospheric) are due to the effort to pump the air through grain; that is, the energy requirements for the ambient air system are attributed to the friction loss of the air through the grain. Increasing the grain depth or the airflow or both would result in increased energy requirements. The rate of increase; however, is greater for pressures above atmospheric than below. In other words, the greater the depth of grain or airflow, the higher the energy requirements for either exhausting or pressurizing the bin but the rate of increase is less for exhausting than for pressurizing. The reason for this is noted later.

The energy requirements increase as the initial moisture content of grain decreases[1] as shown in figures 3, 4, and 5. This relationship is attributed to the variation in the bonding forces within the kernel holding the moisture. For wet grain the water vaporizes as it does from a liquid surface but for dry grain the water is held with considerable force. This increase was observed for both the above and below atmospheric pressures; however, the increase

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[1]The energy to dry given quantity of grain increases with an increase in initial moisture content.

for pressures above atmospheric was higher than for pressures below atmospheric.

The energy requirements increase as the drying season proceeds, mainly due to the drop in ambient air temperature. Average daily air temperatures drop from about 15.5 to 4.4°C at Edmonton during the period August to October thereby reducing the drying potential of the air. The increase in energy requirements is slightly greater for pressures above atmospheric than below (figures 3, 4, and 5). For example, a comparison of figures 3 and 5 indicates that the energy requirements increased 50% for the period August to October for a pressure above atmospheric against a 40% increase for the same pressure below atmospheric.

More important than the above is the indication from figures 3, 4, and 5 that less energy per kilogram of moisture removed is required by operating at pressures below atmospheric than above. This can be further illustrated in figures 6, 7, and 8 where efficiency gain was used to express the advantage in using pressures less than atmospheric. In these figures the pressures above and below atmospheric are replaced with appropriate depths of grain as indicated in chapter 3 namely 1.0, 1.3, and 1.6 meters. The efficiency gain is defined as the difference in energy requirements between the two systems expressed as a percentage of the energy requirements of the system using pressures above atmospheric. The figures show that efficiency gain increases with the depth of grain. This

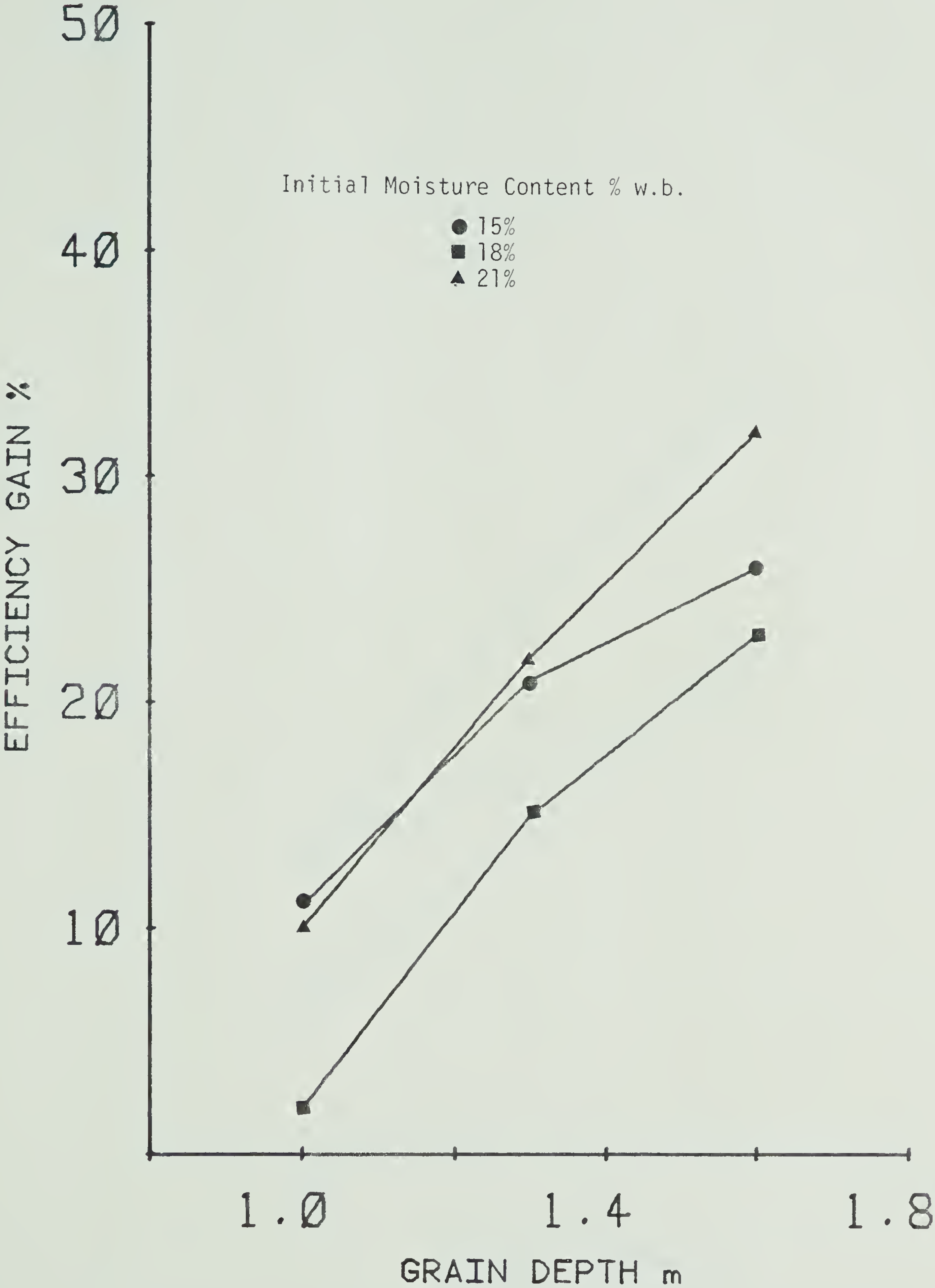

Figure 6: Gain in Drying Efficiency by exhausting the bin rather than pressurizing during August

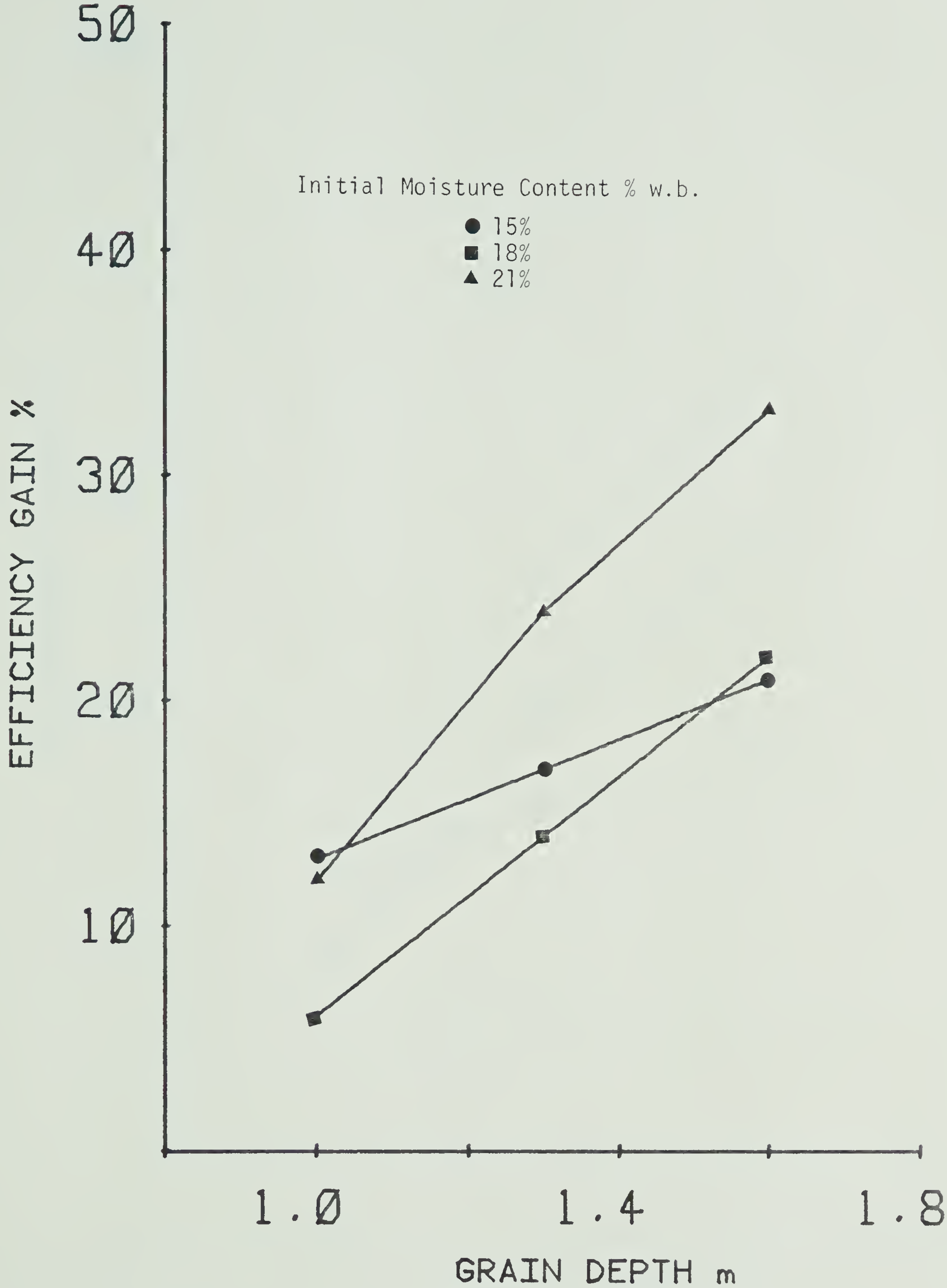

Figure 7: Gain in Drying Efficiency by exhausting the bin rather than pressurizing during September

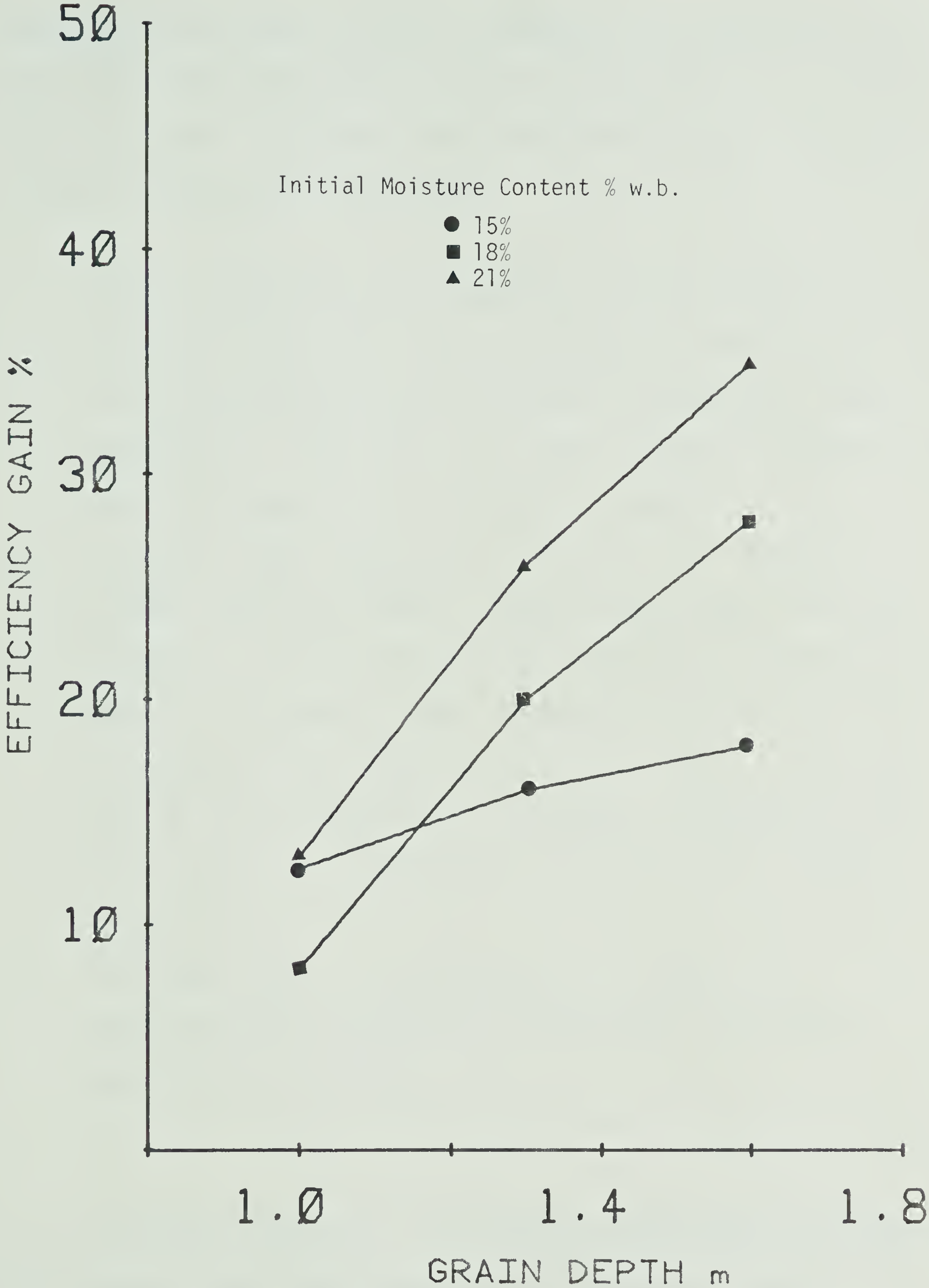

Figure 8: Gain in Drying Efficiency by exhausting the bin rather than pressurizing during October

suggests that using the fan to exhaust a bin type drier is more efficient than using the fan to pressurize it, and the efficiency gain increases with the depth of grain. The gain is attributed to the following :

1. Heat is acquired from the surroundings during the isothermal expansion (below atmospheric) and is lost to the surroundings during isothermal compression (above atmospheric); therefore, the heat energy for exhausting the bin is less than for pressurizing it.
2. A greater vapor pressure differential is created between the grain and its surroundings when the total pressure is reduced below the atmospheric pressure and due to this greater vapor pressure differential, the difference in the humidity ratios of the air entering and the air leaving grain is greater; therefore, more moisture can be removed from the grain with the same amount of air.
3. The latent heat of vaporization is lower for pressures below atmospheric than above; therefore, requiring less energy.

As stated previously, the energy requirements increase at a greater rate when pressures are increased above atmospheric than when decreased an equal amount below atmospheric. This may be explained by examining each system

separately. In case of the above atmospheric pressure system when the pressure is increased (either by increasing grain depth or the airflow), the resistance offered by the grain increases greatly; which causes the energy requirements to increase at a substantial rate. With the below atmospheric system when the pressure is further decreased, the energy requirements to operate the system increase; however, the vapor pressure differential created also increases. This increase in vapor pressure differential partially offsets the higher energy requirements due to a higher airflow or greater grain depth; hence, the resulting increase in the energy requirements for exhausting is less than for pressurizing.

5. SUMMARY AND CONCLUSIONS

The energy requirements for drying wheat during the period August through November at three above and four below atmospheric pressures for the ambient air conditions prevailing near Edmonton, Alberta, were calculated. The basis for calculating the energy requirements was the amount of heat energy required to remove one kilogram of water from grain. An empirical equation from Pfost et at (1976) and a set of equations from ASHRAE (1977) were used respectively to calculate the equilibrium relative humidity and the various psychrometric properties of the air entering and leaving grain. The energy required to pump the air through grain was calculated by assuming an airflow and several pressure losses. The heat energy per unit of moisture removed (kJ/kg water removed) was determined by dividing the energy by the drying capacity. Based on these calculations, the following conclusions are drawn :

1. The energy requirements for drying are less at pressures below atmospheric than above.
2. The energy requirements increase at a greater rate for pressures above atmospheric than below as the the depth of grain or airflow is increased.
3. Drying can continue (to 14% moisture content) for more hours per day, and even on a 24 hour basis, using pressures below atmospheric for the usual drying period in Western Canada.

4. Number of days required to dry wheat to 14% moisture content are generally less for pressures below atmospheric.
5. The energy efficiency is greater for pressures below atmospheric than above and this differential increases for decreasing initial moisture content.
6. The energy efficiency decreases as the drying season proceeds but the decline proceeds at a slightly lower rate for pressures below atmospheric than above.

6. SUGGESTIONS FOR FURTHER STUDY

The following suggestions could prove useful in further investigating and improving the drying efficiency of the low pressure drying system. Firstly, an experimental drier should be designed and tested at certain above and below atmospheric pressures used in this study; such as, 86.7, 91.8, 95.2, and 98.5 kPa. Some additional pressures may be included in the study to enhance the application of the results. These pressures can be established by using different grain depths and/or airflow rates. The grain depth or airflow values considered should be the one commonly used in Western Canada for the conventional manner of ambient air drying; that is, to pressurize the grain bin. The experimental-set up should measure the energy input for moving air through the grain, the dry-bulb and dew-point temperatures, and the moisture loss from the grain. The possibility of heating the air a few degrees above ambient during the adverse weather conditions which increases the drying potentional of the air may also be considered.

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APPENDIX A

Hourly Dry and Wet-Bulb Temperatures (F) prevailing near Edmonton, Alberta during the four drying months of August through November, as given by Cudbird (1964) for 24 hours starting at midnight

AUGUST

D.B. Temperatures : 56.5,55.5,54.5,53.8,53.0,52.4,
52.3,54.1,56.8,59.7,62.1,63.9,65.9,67.1,68.1,68.7,
68.7,68.5,67.3,65.6,62.9,60.7,58.9,57.7

W.B. Temperatures : 52.9,52.2,51.7,51.1,50.5,50.1,
50.2,51.4,52.9,54.4,55.5,56.0,56.7,57.0,57.3,57.4,
57.3,57.3,57.0,56.6,55.8,55.0,54.2,53.5

SEPTEMBER

D.B. Temperatures : 47.5,46.5,45.6,44.8,44.1,43.6,
42.8,43.4,45.7,48.7,51.7,53.9,56.1,57.7,58.8,59.3,
59.1,58.7,56.7,54.0,51.9,50.2,48.9,48.1

W.B. Temperatures : 44.0,43.4,42.8,42.2,41.8,41.4,
40.9,41.3,42.9,44.7,46.3,47.3,48.3,48.9,49.2,49.3,
49.4,49.2,48.4,47.3,46.3,45.4,44.7,44.3

OCTOBER

D.B. Temperatures : 37.6,36.7,36.0,35.4,34.9,34.6,
34.1,34.0,35.0,37.8,41.1,43.6,46.3,48.0,49.0,49.5,
49.0,47.6,44.7,42.9,41.4,40.0,39.0,38.2

W.B. Temperatures : 34.3,33.7,33.2,33.8,32.4,32.1,
31.8,31.7,32.5,34.5,36.5,38.0,39.5,40.2,40.6,40.8,
40.6,39.9,38.4,37.5,36.6,35.8,35.1,34.6

NOVEMBER

D.B. Temperatures : 23.9,23.5,23.1,22.9,22.6,22.4,
22.0,22.0,22.0,22.9,24.9,26.7,29.2,30.7,31.5,31.4,
30.4,28.9,27.4,26.5,25.6,25.0,24.5,24.1

W.B. Temperatures : 22.0,21.7,21.4,21.2,20.9,20.8,
20.6,20.4,20.4,21.1,22.5,23.9,25.7,26.7,27.3,27.3,
26.6,25.7,24.7,24.0,23.4,22.9,22.4,22.1

APPENDIX B

```
C    The program ERH was used to calculate the
C    Equilibrium Relative Humidities for wheat
C    under the ambient temperatures and various
C    initial moisture contents as noted in chapter 3
C
      DIMENSION A(24),B(24),T(24)
      REAL MW(9),MD(9),ERH(9)
      INTEGER I,J
      D=529.43
      B=17.609
      C=50.998
      READ(5,10) (A(I),I=1,24),(B(I),I=1,24)
   10 FORMAT(F5.3)
      READ(5,11) (MW(J),J=1,9)
   11 FORMAT(9F4.2)
      DO 30 I=1,24
      T(I)=(A(I)-32.)*5./9.
      DO 12 J=1,9
      MD(J)=100.*MW(J)/(100.-MW(J))
      MD(J)=MD(J)/100.
      ERH(J)=EXP((-D/(T(I)+C))*EXP(-B*MD(J)))*100.0
   12 CONTINUE
      TEMP=A(I)
      TEMP1=B(I)
      WRITE(6,20) (TEMP1,TEMP,(ERH(J),J=1,9))
   20 FORMAT(11F8.1)
   30 CONTINUE
      STOP
      END
```

APPENDIX C-1

Equilibrium Relative Humidities ERH (%) for August

Temperatures wet-bulb (F)	dry-bulb (F)	Moisture Content % wet basis 22	21	20	19	18	17	16	15	14
52.9	56.5	94.5	92.7	90.4	87.7	84.2	80.1	75.1	69.3	62.7
52.2	55.5	94.4	92.6	90.4	87.6	84.1	79.9	74.9	69.1	62.5
51.7	54.5	94.4	92.6	90.3	87.5	84.0	79.7	74.7	68.9	62.2
51.1	53.8	94.3	92.5	90.2	87.4	83.9	79.6	74.6	68.7	62.0
50.5	53.0	94.3	92.5	90.2	87.3	83.8	79.5	74.4	68.5	61.8
50.1	52.4	94.3	92.4	90.1	87.2	83.7	79.4	74.3	68.4	61.7
50.2	52.3	94.2	92.4	90.1	87.2	83.7	79.4	74.3	68.4	61.7
51.4	54.1	94.3	92.5	90.3	87.4	83.9	79.7	74.7	68.8	62.1
52.9	56.8	94.5	92.7	90.5	87.7	84.3	80.1	75.2	69.4	62.8
54.4	59.7	94.6	92.9	90.7	88.0	84.6	80.5	75.7	70.0	63.5
55.5	62.1	94.7	93.0	90.9	88.2	84.9	80.9	76.1	70.5	64.1
56.0	63.9	94.8	93.1	91.0	88.4	85.1	81.1	76.4	70.9	64.5
56.7	65.9	94.9	93.2	91.1	88.5	85.3	81.4	76.7	71.2	65.0
57.0	67.1	94.9	93.3	91.2	88.6	85.4	81.6	76.9	71.5	65.2
57.3	68.1	94.9	93.3	91.3	88.7	85.5	81.7	77.1	71.7	65.4
57.4	68.7	95.0	93.4	91.3	88.8	85.6	81.8	77.2	71.8	65.6
57.3	68.7	95.0	93.4	91.3	88.8	85.6	81.8	77.2	71.8	65.6
57.3	68.5	95.0	93.3	91.3	88.7	85.6	81.7	77.1	71.7	65.5
57.0	67.3	94.9	93.3	91.2	88.6	85.5	81.6	77.0	71.5	65.3
56.6	65.6	94.8	93.2	91.1	88.5	85.3	81.4	76.7	71.2	64.9
55.8	62.9	94.7	93.1	90.9	88.3	85.0	81.0	76.2	70.7	64.3
55.0	60.7	94.6	92.9	90.8	88.1	84.7	80.7	75.9	70.2	63.8
54.2	58.9	94.6	92.8	90.6	87.9	84.5	80.4	75.5	69.8	63.3
53.5	57.7	94.5	92.8	90.5	87.8	84.4	80.2	75.3	69.6	63.0

APPENDIX C-2

Equilibrium Relative Humidities ERH (%) for September

Temperatures		Moisture Content % wet basis								
wet-bulb (F)	dry-bulb (F)	22	21	20	19	18	17	16	15	14
44.0	47.5	94.0	92.1	89.7	86.7	83.0	78.6	73.3	67.2	60.3
43.4	46.5	93.9	92.0	89.6	86.6	82.9	78.4	73.1	67.0	60.0
42.8	45.6	93.9	92.0	89.5	86.5	82.7	78.2	72.9	66.7	59.8
42.2	44.8	93.9	91.9	89.4	86.4	82.6	78.1	72.7	66.5	59.6
41.8	44.1	93.8	91.8	89.4	86.3	82.5	78.0	72.6	66.4	59.3
41.4	43.6	93.8	91.8	89.3	86.2	82.4	77.9	72.5	66.2	59.2
40.9	42.8	93.7	91.7	89.2	86.1	82.3	77.7	72.3	66.0	59.0
41.3	43.4	93.8	91.8	89.3	86.2	82.4	77.8	72.4	66.2	59.1
42.9	45.7	93.9	92.0	89.5	86.5	82.8	78.3	72.9	66.8	59.8
44.7	48.7	94.1	92.2	89.8	86.8	83.2	78.8	73.6	67.5	60.7
46.3	51.7	94.2	92.4	90.1	87.2	83.6	79.3	74.2	68.2	61.5
47.3	53.9	94.3	92.5	90.2	87.4	83.9	79.7	74.6	68.7	62.1
48.3	56.1	94.4	92.7	90.4	87.6	84.2	80.0	75.0	69.2	62.6
48.9	57.7	94.5	92.8	90.5	87.8	84.4	80.2	75.3	69.6	63.0
49.2	58.8	94.6	92.8	90.6	87.9	84.5	80.4	75.5	69.8	63.3
49.3	59.3	94.6	92.9	90.7	87.9	84.6	80.5	75.6	69.9	63.4
49.4	59.1	94.6	92.8	90.6	87.9	84.5	80.4	75.6	69.9	63.4
49.2	58.7	94.6	92.8	90.6	87.9	84.5	80.4	75.5	69.8	63.3
48.4	56.7	94.5	92.7	90.5	87.7	84.2	80.1	75.1	69.4	62.8
47.3	54.0	94.3	92.5	90.3	87.4	83.9	79.7	74.6	68.8	62.1
46.3	51.9	94.2	92.4	90.1	87.2	83.6	79.3	74.2	68.3	61.5
45.4	50.2	94.1	92.3	89.9	87.0	83.4	79.0	73.9	67.9	61.1
44.7	48.9	94.1	92.2	89.8	86.9	83.2	78.8	73.6	67.6	60.7
44.3	48.1	94.0	92.1	89.7	86.8	83.1	78.7	73.4	67.4	60.5

APPENDIX C-3

Equilibrium Relative Humidities ERH (%) for October

Temperatures wet-bulb (F)	Temperatures dry-bulb (F)	Moisture Content % wet basis 22	21	20	19	18	17	16	15	14
34.3	37.6	93.4	91.3	88.7	85.4	81.5	76.7	71.0	64.6	57.3
33.7	36.7	93.4	91.3	88.6	85.3	81.3	76.5	70.8	64.3	57.0
33.2	36.0	93.3	91.2	88.5	85.2	81.2	76.3	70.6	64.1	56.8
33.8	35.4	93.3	91.1	88.5	85.1	81.1	76.2	70.5	63.9	56.6
32.4	34.9	93.2	91.1	88.4	85.1	81.0	76.1	70.4	63.8	56.4
32.1	34.6	93.2	91.1	88.4	85.0	80.9	76.0	70.3	63.7	56.3
31.8	34.1	93.2	91.0	88.3	84.9	80.8	75.9	70.1	63.5	56.1
31.7	34.0	93.2	91.0	88.3	84.9	80.8	75.9	70.1	63.5	56.1
32.5	35.0	93.2	91.1	88.4	85.1	81.0	76.1	70.4	63.8	56.4
34.5	37.8	93.4	91.3	88.7	85.5	81.5	76.7	71.1	64.6	57.4
36.5	41.1	93.6	91.6	89.1	85.9	82.0	77.4	71.9	65.6	58.4
38.0	43.6	93.8	91.8	89.3	86.2	82.4	77.9	72.5	66.2	59.2
39.5	46.3	93.9	92.0	89.6	86.6	82.8	78.4	73.1	66.9	60.0
40.2	48.0	94.0	92.1	89.7	86.8	83.1	78.7	73.4	67.3	60.5
40.6	49.0	94.1	92.2	89.8	86.9	83.2	78.8	73.6	67.6	60.8
40.8	49.5	94.1	92.2	89.9	86.9	83.3	78.9	73.7	67.7	60.9
40.6	49.0	94.1	92.2	89.8	86.9	83.2	78.8	73.6	67.6	60.8
39.9	47.6	94.0	92.1	89.7	86.7	83.0	78.6	73.3	67.2	60.4
38.4	44.7	93.8	91.9	89.4	86.4	82.6	78.1	72.7	66.5	59.5
37.5	42.9	93.7	91.8	89.3	86.1	82.3	77.7	72.3	66.0	59.0
36.6	41.4	93.7	91.6	89.1	86.0	82.1	77.4	72.0	65.6	58.5
35.8	40.0	93.6	91.5	89.0	85.8	81.9	77.2	71.6	65.2	58.1
35.1	39.0	93.5	91.4	88.9	85.6	81.7	77.0	71.4	65.0	57.8
34.6	38.2	93.4	91.4	88.8	85.5	81.6	76.8	71.2	64.7	57.5

APPENDIX C-4

Equilibrium Relative Humidities ERH (%) for November

Temperatures wet-bulb (F)	dry-bulb (F)	Moisture Content % wet basis 22	21	20	19	18	17	16	15	14
22.0	23.9	92.4	90.0	87.0	83.3	78.8	73.4	67.2	60.1	52.3
21.7	23.5	92.3	89.9	86.9	83.2	78.7	73.3	67.0	60.0	52.2
21.4	23.1	92.3	89.9	86.9	83.1	78.6	73.2	66.9	59.8	52.0
21.2	22.9	92.3	89.9	86.8	83.1	78.5	73.1	66.9	59.7	51.9
20.9	22.6	92.3	89.8	86.8	83.0	78.5	73.1	66.8	59.6	51.8
20.8	22.4	92.2	89.8	86.8	83.0	78.4	73.0	66.7	59.5	51.7
20.6	22.0	92.2	89.8	86.7	82.9	78.3	72.9	66.6	59.4	51.5
20.4	22.0	92.2	89.8	86.7	82.9	78.3	72.9	66.6	59.4	51.5
20.4	22.0	92.2	89.8	86.7	82.9	78.3	72.9	66.6	59.4	51.5
21.1	22.9	92.3	89.9	86.8	83.1	78.5	73.1	66.9	59.7	51.9
22.5	24.9	92.5	90.1	87.1	83.5	79.0	73.7	67.5	60.5	52.7
23.9	26.7	92.6	90.3	87.4	83.8	79.4	74.2	68.0	61.1	53.4
25.7	29.2	92.8	90.5	87.7	84.2	79.9	74.8	68.8	62.0	54.4
26.7	30.7	92.9	90.7	87.9	84.4	80.2	75.1	69.2	62.4	54.9
27.3	31.5	93.0	90.8	88.0	84.6	80.4	75.3	69.4	62.7	55.2
27.3	31.4	93.0	90.8	88.0	84.5	80.3	75.3	69.4	62.7	55.2
26.6	30.4	92.9	90.7	87.9	84.4	80.1	75.1	69.1	62.3	54.8
25.7	28.9	92.8	90.5	87.7	84.1	79.8	74.7	68.7	61.9	54.3
24.7	27.4	92.7	90.4	87.5	83.9	79.5	74.3	68.3	61.3	53.7
24.0	26.5	92.6	90.3	87.3	83.7	79.3	74.1	68.0	61.0	53.4
23.4	25.6	92.5	90.2	87.2	83.6	79.1	73.9	67.7	60.7	53.0
22.9	25.0	92.5	90.1	87.1	83.5	79.0	73.7	67.5	60.5	52.8
22.4	24.5	92.4	90.0	87.1	83.4	78.9	73.6	67.4	60.3	52.6
22.1	24.1	92.4	90.0	87.0	83.3	78.8	73.5	67.2	60.2	52.4

APPENDIX D

```
C   The program PSYALL performs psychrometric
C   calculations during the drying process when
C   pressure surrounding grain is below atmospheric
C
      LOGICAL*1 LIS(1)/'*'/
      DIMENSION ERH(9)
      WRITE(6,4)
    4 FORMAT('1TIME MOIS  BARO  ENTH  TWET  TIN   TOUT',
     1'  DELT  WIN  WOUT  DELW  ERH'/)
      WRITE(7,96)
   96 FORMAT('ENTER THE REDUCED PRESSURE.')
      READ(7,LIS) B2
C   B2 = (Bfan + Batm)/2.0
C   assume linear pressure gradient
      DO 9999 J=1,24
      B=27.6
      READ(5,3) TW,T1,(ERH(I),I=1,9)
      WRITE(7,3) TW,T1,(ERH(I),I=1,9)
    3 FORMAT(F4.1,10F8.1)
COMPUTE
      CALL PRESS(T1,PS)
      CALL PRESS(TW,PX)
      WX=.622*PX/(B-PX)
      H=.24*TW+WX*(1061.+.45*TW)
      W1=(H-.24*T1)/(1061.+(.45*T1))
Completed the first step - At this stage, we have inlet
C   absolute humidity W1 and enthalpy H. Now decrease
C   the pressure.  The enthalpy of air will change
C   because of the heat gained (Q) from the
C   surroundings due to isothermal expansion.
      TH1=H/0.24
      Q=(53.3*(T1+460.0)*ALOG(B/B2))/778.
      HBAR=H+Q
      TH2=HBAR/0.24
      DELH=TH2-TH1
      TBAR=T1+DELH
C   HBAR and TBAR are new values of enthalpy
C   and temperature of air at low pressure.
C
C   DO LOOP for calculating the absolute humidity
C   of air (WOUT) leaving grain at the ERH.
      DO 900 I=1,9
      TM= HBAR/.24
      X=1.0
   21 TM=TM-X
      CALL PRESS(TM,PS)
      W=(HBAR-.24*TM)/(1061.+(.45*TM))
      WS=.622*PS/(B2-PS)
C     CALL RELHUM(B2,W,WS,PS,R1)
```

continued .....

```
      U=W/WS
      IF(U.GT.1.) U=1.
      RH=100.*U/(1.-((1.-U)*(PS/B2)))
      IF(RH.LT.ERH(I)) GO TO 21
      IF(X.EQ.0.1) GO TO 23
      TM=TM+X
      X=X/10
      GO TO 21
   23 CONTINUE
C     -----------OUTPUT------------
      W=W*1000.
      W1=W1*1000.
      DELW=W-W1
      DELT=TBAR-TM
      L=23-I
      WRITE(6,34) J,L,B2,H,TW,T1,TM,DELT,W1,W,DELW,ERH(I)
   34 FORMAT(1X,I2,5X,I2,1X,10F10.2)
      W1=W1/1000
  900 CONTINUE
 9999 CONTINUE
      STOP
      END
C     -----Functions and subroutines-----
      SUBROUTINE PRESS(T,PP)
      TT=273.16/(((T-32.)*5./9.)+273.16)
      IF(T.LT.32.) GO TO 1
      P=10.**(10.79586*(1.-TT)+5.02808*ALOG10(TT)
     1+1.50474E-4*(1.-10**(-8.29692*((1./TT)-1.)))
     2+0.42873E-3*(10.**(4.76955*(1.-TT))-1.)-2.219598)
      GO TO 2
    1 P=10.**(-9.096936*(TT-1.)-3.56654*ALOG10(TT)
     1+0.876817*(1.-(1./TT))-2.219598)
    2 PP=P*29.921
      RETURN
      END
```

APPENDIX E

```
C   The program PSYALL1 performs psychrometric
C   calculations during the drying process when
C   pressure surrounding grain is above atmospheric
C
      LOGICAL*1 LIS(1)/'*'/
      DIMENSION ERH(9)
      WRITE(6,4)
    4 FORMAT('1TIME MOIS  BARO  ENTH  TWET  TIN   TOUT',
     1'  DELT  WIN  WOUT  DELW  ERH'/)
      WRITE(7,96)
   96 FORMAT('ENTER THE INCREASED PRESSURE.')
      READ(7,LIS) B2
C   B2 = (Bfan + Batm)/2.0
C   assume linear pressure gradient
      DO 9999 J=1,24
      B=27.6
      READ(5,3) TW,T1,(ERH(I),I=1,9)
      WRITE(7,3) TW,T1,(ERH(I),I=1,9)
    3 FORMAT(F4.1,10F8.1)
COMPUTE
      CALL PRESS(T1,PS)
      CALL PRESS(TW,PX)
      WX=.622*PX/(B-PX)
      H=.24*TW+WX*(1061.+.45*TW)
      W1=(H-.24*T1)/(1061.+(.45*T1))
Completed the first step - At this stage, we have inlet
C   absolute humidity W1 and enthalpy H.
C   Now air enters grain where the pressure is
C   above atmospheric and W1 & H remains unchanged.
C
C   DO LOOP for calculating the absolute humidity WOUT
C   and temperature TOUT of air leaving grain at ERH.
C
      DO 900 I=1,9
      TM= H/.24
      X=1.0
   21 TM=TM-X
      CALL PRESS(TM,PS)
      W=(H-.24*TM)/(1061.+(.45*TM))
      WS=.622*PS/(B2-PS)
C     CALL RELHUM(B2,W,WS,PS,R1)
      U=W/WS
      IF(U.GT.1.) U=1.
      RH=100.*U/(1.-((1.-U)*(PS/B2)))
      IF(RH.LT.ERH(I)) GO TO 21
      IF(X.EQ.0.1) GO TO 23
      TM=TM+X
      X=X/10
      GO TO 21
```

continued .....

```
   23 CONTINUE
C    --------OUTPUT--------
      W=W*1000.
      W1=W1*1000.
      DELW=W-W1
      DELT=T1-TM
      L=23-I
      WRITE(6,34) J,L,B2,H,TW,T1,TM,DELT,W1,W,DELW,ERH(I)
   34 FORMAT(1X,I2,5X,I2,1X,10F10.2)
      W1=W1/1000
  900 CONTINUE
 9999 CONTINUE
      STOP
      END
C    -----Functions and subroutines-----
      SUBROUTINE PRESS(T,PP)
      TT=273.16/(((T-32.)*5./9.)+273.16)
      IF(T.LT.32.) GO TO 1
      P=10.**(10.79586*(1.-TT)+5.02808*ALOG10(TT)
     1+1.50474E-4*(1.-10**(-8.29692*((1./TT)-1.)))
     2+0.42873E-3*(10.**(4.76955*(1.-TT))-1.)-2.219598)
      GO TO 2
    1 P=10.**(-9.096936*(TT-1.)-3.56654*ALOG10(TT)
     1+0.876817*(1.-(1./TT))-2.219598)
    2 PP=P*29.921
      RETURN
      END
```

APPENDIX F

```
C     The program FILE1 was used to calculate the energy
C     requirements per kilogram of water removed, the
C     number of hours available each day to dry, and the
C     number of days required to dry wheat to 14% as
C     suggested by Feddes et al. (1980).
C
      DIMENSION DELW(8,24),SUM1(8),SUM2(8),SUM3(8),
     1TEMP(8,24),SUM4(9),SUM5(9),SUM6(9),DELWB(8),
     1TEMPB(8),DELWR(8),TEMPR(8),TR(8),P2(7),AEN(8),
     1AKJ(8),DAYS(8),AA(8),TDELWR(8)
      DATA AA/0.15,0.16,0.17,0.18,0.19,0.20,0.21,0.22/
      DATA P2/29.1,28.6,28.1,27.1,26.6,26.1,25.6/
      DO 99 L=1,7
C I=INITIAL MOISTURE CONTENT
C K=HOUR
      DO 14 K=1,24
      DO 13 I=1,8
      READ(5,11) TEMP(I,K),DELW(I,K)
C     WRITE(7,97) TEMP(I,K),DELW(I,K)
   11 FORMAT(43X,F10.2,40X,F10.2)
C  97 FORMAT(43X,F10.2,40X,F10.2)
   13 CONTINUE
   14 CONTINUE
      DO 10 K=1,8
      SUM1(K)=0.0
      SUM2(K)=0.0
      SUM3(K)=0.0
      SUM4(K)=0.0
      SUM5(K)=0.0
      SUM6(K)=0.0
      DO 20 I=1,24
C SUM1 is sum of humidity ratios per day for each
C  K initial moisture content
C SUM2 is number of drying hours per day for each
C  K initial moisture content
C SUM3 is sum of dry-bulb temperatures when the
C  air has drying potential
      IF(DELW(K,I).GT. 0.0) SUM1(K)=SUM1(K)+DELW(K,I)
      IF(DELW(K,I).GT. 0.0) SUM2(K)=SUM2(K)+1.0
      IF(DELW(K,I).GT. 0.0) SUM3(K)=SUM3(K)+TEMP(K,I)
20    CONTINUE
      DELWB(K)=SUM1(K)/SUM2(K)
      TEMPB(K)=SUM3(K)/SUM2(K)
10    CONTINUE
C
      DO 15 K=1,8
      KK=9-K
      SUM4(K+1)=SUM4(K)+DELWB(KK)
      SUM5(K+1)=SUM5(K)+TEMPB(KK)
```

continued .....

```
      SUM6(K+1)=SUM6(K)+SUM2(KK)
C SUM4 is the accumulative sum of the
C             humidity ratios(DELTA X's)
C SUM5 is the accumulative sum of the
C             dry-bulb temperatures
C SUM6 is the accumulative sum of no of hours
      DIV=K
      P1=27.6
      R=53.3
      AK=1.4
      Q=3.0
C  Q the airflow rate in CFM per bushel
      DELWR(K)=SUM4(K+1)/DIV
      TEMPR(K)=SUM5(K+1)/DIV
      TR(K)=SUM6(K+1)/DIV
      TDELWR(K)=TR(K)*DELWR(K)*60.0/1000.0
C DELWR is the average DELTA X value for various m.c ranges
C TEMPR is the average D.B.TEMP value for various m.c ranges
C TR    is the average NO of HOURS for various m.c ranges
C TDELWR is the product of DELWR & TR. It's units are
C   lb water x min / lb dry air per day
      AEN(K)=ABS((((TEMPR(K)+460.)*R*AK)/(AK-1.0))*
     1((P2(L)/P1)**((AK-1.0)/AK)-1.0))/778.0
      DELM=AA(K)-0.14*(1.0-AA(K))/0.86
      DAYS(K)=(13.0*60.0*DELM)/(Q*TDELWR(K))
      AKJ(K)=(AEN(K)/DELWR(K))*1000.*2.326
C AEN is the energy required to move air through grain
C AKJ is the KJ/Kg of water removed
C DAYS is the number of days to dry grain
15    CONTINUE
C Now output all values for this month and pressure.
      WRITE(6,12) L,(DELWR(K),K=1,8),(TEMPR(K),K=1,8),
     1(TR(K),K=1,8),(AEN(K),K=1,8),(AKJ(K),K=1,8),
     1(DAYS(K),K=1,8)
   12 FORMAT(2X,I4,8F10.2,/8X,8F10.2,/8X,8F10.2,
     1/8X,8F10.2,/8X,8F10.2,/8X,8F10.2)
   99 CONTINUE
      STOP
      END
```

APPENDIX G

Flow chart showing in sequence the different computer programs used to perform various calculations